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BEHAVIORAL DYNAMICS IN THE COOPERATIVE CONTROL OF MIXED HUMAN/ROBOT TE

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14. ABSTRACT
Results are reported on new methods to capture, model, represent, and ultimately understand human behavior in complex and possibly adversarial scenarios involving autonomous and semi-autonomous machine agents. Principles and models of cognitive and social psychology play a major role in the work. A particular objective is to develop a fundamental understanding of how humans and autonomous machine agents can operate as teams to efficiently accomplish mission objectives. An important focus of the research is on how human behavior differs from ideal decision makers due to social factors including pressure to conform, competitiveness, and other aspects of group dynamics. In addition to exploring cognitive and social psychological aspects of decision making, research is focused on formal approaches to communication through action. Understanding how gestures and structured motions can be used to communicate is essential to involving mobile smart machines as team members. An overarching goal is an understanding of how nuanced changes in collective motions of group of mobile agent serve to signal intentions of actions to come. The third major component of the research being reported discusses new results in task partitioning between humans and machines. The three research foci support a paradigm shift that supports the study of teams in which humans operate on parity with automatons.

15. SUBJECT TERMS
human-machine interactions, two-alternative-forced-choice (TAFC), cognitive and social psychological aspects of decision making, action-mediated communication, human/machine parity

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BEHAVIORAL DYNAMICS IN THE COOPERATIVE CONTROL OF MIXED HUMAN/ROBOT TEAMS

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Abstract

This report documents research supported by the U.S. Department of Defense, DDR&E MURI Topic 16, FY 2007 as announced in ONR BAA 06-028. The period of performance was July 1, 2007 through June 30, 2012. Results are reported on new methods to capture, model, represent, and ultimately understand human behavior in complex and possibly adversarial scenarios involving autonomous and semi-autonomous machine agents. Principles and models of cognitive and social psychology play a major role in the work. A particular objective is to develop a fundamental understanding of how humans and autonomous machine agents can operate as teams to efficiently accomplish mission objectives. The research is focused on conditions in human-machine interactions in which humans may not perform well because of excessive workload, inability to assimilate information, and various types of cognitive fatigue such as boredom and decreased attentiveness due to task repetitiveness. An equally important focus of the research is on how human behavior differs from ideal decision makers due to social factors including pressure to conform, competitiveness, and other aspects of group dynamics. In addition to exploring cognitive and social psychological aspects of decision making, research is focused on formal approaches to communication through action. Understanding how gestures and structured motions can be used to communicate is essential to involving mobile smart machines as team members. An overarching goal is an understanding of how nuanced changes in collective motions of group of mobile agent serve to signal intentions of actions to come. The third major component of the research being reported discusses new results in task partitioning between humans and machines. The three research foci support a paradigm shift that supports the study of teams in which humans operate on parity with automatons.

Project Results Summary

The three main components of research supported by the grant are (*i*) decision modeling, (*ii*) action-mediated communication, and (*iii*) task partitioning. Progress on all three of these has

been reported in workshops, technical conferences, and research publications. Synergistic research at the four participating institutions has sought to develop models of decision-making tailored to human-in-the-loop control of mixed human/robot teams. There has been significant progress in modeling human decision dynamics using Ornstein-Uhlenbeck (drift-diffusion) stochastic differential equation models, and recently the team has been working to develop models of search behavior using hidden Markov models as well. The goal in this research has been to develop models of relevant psychological dynamics that can be integrated with the larger body of research supported by the Dynamics and Control Program of AFOSR. Work at the University of Washington and Princeton has shown that for a simple two-alternative forced choice decision game, people tend to play strategies that minimize the variance of a reward while avoiding strategies that would have higher reward payout over a period of play. We have shown that this tendency to be risk averse appears in the stochastic models of human behavior as well. At Boston University, results have been reported on search strategies for mixed teams of humans and sensor-enabled robots. Computer generated Gaussian random fields have been used to construct synthetic environments in a computer game in which the players conduct reconnaissance missions with the goal of mapping the unknown field. In part this study has focused on studying alternative human roles in interactions with control algorithms in mixed human/robot teams. Drawing inspiration from early work by N. Leonard and coworkers, Baronov and Baillieul have developed feedback control laws for sensor-enabled mobile robots that can steer the robots along paths that trace curves of constant value of a scalar potential field. Control laws for ascending and descending a potential field gradient have been developed as well. By appropriately switching between these two kinds of control, sensor-enabled mobile robots can map the values of an unknown potential field to any desired degree of accuracy. This mapping provides a useful abstraction for the exploration of quantities that vary over a planar domain and that can be sensed by mobile agents moving in the domain. Examples of such quantities include ocean temperature, CO_2 concentration, magnetic fields, and so forth.

In the studies that have been conducted, The strategies that emerge from the choices of motion sequences are classified in terms of the speed with which information is acquired, the fidelity with which the acquired information represents the entire field, and the extent to which all critical level sets have been approximated. The game thus records each player's performance in acquiring information about both the topology and geometry of the unknown fields that have been randomly generated. Results so far indicate that human subjects consciously or unconsciously prefer to seek topological (as opposed to metric) information in their reconnaissance missions. This work has been reported in a paper appearing in focused special issue of the *Proceedings of the IEEE* (Vol. 100:3, March, 2012, pp. 776-801. DOI:10.1109/JPROC.s011.2174101).

Progress has been made in our study of communication through action. We have developed formal protocols for communication based on gestures and modulating the relative motion between mobile agents. This type of communication is dependent on context in that a particular motion or gesture will indicate something related to the current activity. The focus of the work is on enabling motion-based signaling between mobile agents that use motions and gestures that are multiplexed with mission-critical motions. Classes of motion control laws that enables such signaling have been developed and analyzed. Properties of signals that are amenable to such signaling have been studied, and we have found error bounds on the sensing of such motion based signaling. Current work involves developing the foundations of multiagent action-

mediated control using new concepts in what has been called *control communication complexity*. In his seminal paper, “Control Communication Complexity of Distributed Control Systems,” 48:3 pp.~1722--1742, 2009, W.S. Wong extended A.C. Yao’s concept of communication complexity in a very natural way to a setting in which agents communicate with each other by collaboratively operating a digital finite communication bandwidth (DFCB) control system. Research over the past year under the subject project has been aimed at exploring similar ideas in the setting of time invariant linear control systems and in the case of an broad and important class of nonlinear systems with classes of standard inputs.

The team has made progress in its multidisciplinary effort to better understand social influence in decision-making for groups of humans. Analytic predictions of steady-state performance were derived for multiple decision makers in a two-alternative forced choice task with social feedback. An experiment was designed to test predictions with a directed interaction network and with both human and machine decision makers. A second experiment has been completed which examines the separable influences of information from a spatial environment and from other agents. Preliminary analyses of behavioral and neuroimaging data has yielded promising results. Bayesian models have been developed to describe how subjects learn, exploit and explore in this experiment.

We considered the problem of sensor selection for time-optimal binary detection. We have studied a group of sensors sequentially transmitting their observations to a fusion center. The fusion center considers the output of only one sensor at the time. For three distinct performance metrics, we have shown that the fusion center almost surely needs to look at at-most two sensors. In ongoing work, we are considering a number of generalizations to multi-hypothesis testing problems, quickest change detection and distributed architectures without fusion centers.

The sensor selection task was broken down into three inter-related topics. First, we considered sensor selection problems for time-optimal binary detection; for a variety of distinct performance metrics, we showed that it suffices to focus attention on a subset of sensors. We recently developed (1) an adaptive scheme that is provably optimal in noisy situations, and (2) a vehicle routing algorithm that exploits our sensor selection scheme together with convex optimization ideas to design UAV surveillance strategies. Second, we developed a comprehensive analysis of cooperative decision making in fully distributed settings without any leader. Results included the complete analysis of "sequential decision aggregation" when no interactions occur between the agents, and this led to the development of a novel tractable model for the case in which agents are subject to social peer pressure. Third, as an example of distributed decision making we developed distributed algorithms on source localization via partitioning.

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See “Publications” listed below.

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Conference Abstracts:

D. Tomlin, A. Nedic, D.A. Prentice, P. Holmes and J.D. Cohen (2009). Neural responses to social feedback during group decision making. Society for Neuroscience meeting, Chicago, IL, Oct 17-21, 2009. [not included in 2010 report]

A. Nedic (2010) A decision task in a social context: Behavioral experiments, models, and analyses of behavioral data. Poster presentation at Sloan-Swartz Centers Meeting, Yale University, June 28-July 1, 2010.

D. Tomlin, A. Nedic, D.A. Prentice, P. Holmes and J.D. Cohen (2010). Group Foraging Task Reveals Neural Substrates of Social Influence. Society for Neuroscience meeting, San Diego, CA, Nov 13-17, 2010.

Honors & Awards Received

Plenary lecture: "Integrating human and robot decision-making dynamics," Naomi Ehrich Leonard, MTNS 2008, Blacksburg, VA, Tuesday, July 29.

Plenary lecture: "The Psychology of Human-Robot Interaction," John Baillieul, The International Conference on Instrumentation, Control, and Information Technology-SICE 2008, Chofu, Tokyo, Japan, August 22.

Plenary lecture: "The physics of decision making: Stochastic ODEs as models for neural dynamics and evidence accumulation in cortical circuits," Phil Holmes, XVI International Congress on Mathematical Physics, Prague, August 3-8,2009.

Francesco Bullo's paper with J. Cortes and S. Martinez, entitled "Motion Coordination with Distributed Information" won the 2008 Outstanding Paper Award for the *IEEE Control Systems Magazine*.

Francesco Bullo's paper with J. Cortes, entitled "Coordination and Geometric Optimization via Distributed Dynamical Systems," *SIAM J. on Control & Optimization*, 44(3), 2005, was selected for the SIGEST section of *SIAM Review.*

John Baillieul was elected to the inaugural class of SIAM Fellows in 2009.

Naomi Leonard was named Edwin S. Wilsey Professor of Mechanical and Aerospace Engineering at Princeton in 2008.

Kristi Morgansen was elected to tenure and promoted to Associate Professor (effective September 16, 2009) at the University of Washington

P. Holmes (2010) "The neurodynamics of simple decisions: Drift-diffusion equations as models for single brains, and for group behaviors." Invited plenary lecture at *SIAM Conference on the Life Sciences*, Pittsburgh, PA, July 12-15, 2010.

N.E. Leonard (2009) "Flocks and fleets: Collective motion in nature and robotics, Invited public lecture," Princeton President's Lecture Series, Princeton, NJ, October 22, 2009.

N.E. Leonard (2009) "Stability and robustness of collective dynamics," Plenary lecture, Canadian Mathematical Society Winter Meeting, Windsor, Ontario, Canada, December 7, 2009.

N.E. Leonard (2010) "Cooperative control and mobile sensor networks in the ocean," Semi-plenary lecture, *American Control Conference*, Baltimore, MD, July 2, 2010.

Jonathan Cohen won the 2010 annual Distinguished Scientific Contribution Award of the

American Psychological Association.

Philip Holmes won the 2009 Liapunov Award of the American Society of Mechanical Engineers for lifetime contributions to the field of applied nonlinear dynamics.

Linh Vu and Kristi A. Morgansen received the 2010 O. Hugo Schuck Award for Best Theory paper at the 2009 American Control Conference: "Stability of Feedback Switched Systems with State and Switching Delays"

Phil Holmes elected SIAM Fellow (2011)

John B. elected IFAC Fellow (2011)

Phil Holmes to receive the T.K. Caughey Award from ASME Applied Mech. Div. Fall 2011

Francesco Bullo won the 2010 Hugo Schuck Best Paper Award, AACC

John B. to receive the IEEE Control Systems Society Bode Lecture Prize in December, 2011

Francesco Bullo to deliver plenary address at the SIAM Conf. on Control & Its Appl., Baltimore, MD, Jul 2011

- keynote address at 2nd IFAC Workshop on Distributed Estimation and Control in Networked Systems, Annecy, France, Sep 2010

Phil Holmes was Opening Plenary Speaker, SIAM Conference on Life Sciences, Pittsburgh, PA, July 12-15, 2010

- invited talk at the International Congress on Industrial and Applied Mathematics, Vancouver, BC, July 18-22, 2011

John Baillieul was keynote speaker "Information Based Control and Control Communication Complexity," 2011 Asian Control Conference, Kaohsiung, Taiwan, May 17, 2011

Transitions

- CDC 2008, December 9-11, Cancun, MX: Invited Session: Mixed Robot/Human Team Decision Dynamics
- ACC 2010, June 30 - July 2, Baltimore, MD: Invited Session: Humans-In-The-Loop Control Systems
- CDC 2010, December 15-17, Atlanta, GA: Invited Session: The control theory of robot-assisted exploration of scalar potential fields
- NSF CMMI Workshop on Neuromechanical Engineering, September 14-15: Baillieul delivered one of five keynote talks: Cognitive Aspects of Simple Decisions in Search and Reconnaissance

- United Technologies Research Center, August 17, 2010, The Boston University team will have a daylong visit with UTRC research staff to discuss research supported by the MURI
- Special Issue of the Proceedings of the IEEE on Interaction Dynamics at the Interface of Humans and Smart Machines, Eds: Baillieul, Leonard, Morgansen. Publication target: November, 2011
- Keynote talk "Information Based Control and Control Communication Complexity," 2011 Asian Control Conference, Kaohsiung, Taiwan, May 17, 2011
- 2011 Control Systems Society Bode Lecture, "Fifty Years of Information Based Control Theory," To be delivered by John Baillieul at the 50th IEEE Conference on Decision and Control, December, 2011.